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Influence of furnishing on indoor airflow near external walls

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SUMMARY
Simulations of indoor environments in buildings are usually performed assuming uniform distribution of temperature and humidity of the indoor air, such as it would be in an idealised unfurnished room. The flow patterns near external walls may however be very different from the undisturbed airflow distributions, as the walls behind furniture may be colder than the other surroundings of the room, and the furniture to some extent obstructs the airflow.

This paper describes an investigation of a room with a piece of furniture placed near an external wall. This was investigated using Particle Image Velocimetry (PIV) measurements. It was found how the pattern of airflow behind furniture placed near cold walls was influenced by the thickness of air gaps behind and below the furniture. But it was also found that even if the furniture was placed directly on the floor, there would be a considerable flow of air behind the furniture.

KEYWORDS
PIV, Boundary conditions, Airflow velocity, Measurements, Natural convection

INTRODUCTION

Background
Moisture interactions between room air and the surrounding constructions and furniture have a great influence on the indoor environment. High moisture production or cold areas can cause high relative humidity, which may lead to mould growth. This is unwanted in the indoor environment due to concern for the indoor air quality. A review study of humidity in dwellings was performed by Bornehag et al. (2001) and their advice is to avoid moist buildings.

The critical areas in dwellings typically occur in bedrooms, where problems may appear in microclimates behind furniture placed next to exterior walls without or with poor insulation. In dwellings with problems, the surface temperature of the exterior wall is typically 5-8 °C colder than the room temperature. It is assumed that the furniture limits the airflow near the wall and the lack of warm room air near the surface will decrease the surface temperature even more, which can cause problems. When this is combined with a high moisture production rate from sleeping persons during night, the lower temperature in the microclimate causes increased relative humidity, and the outcome can be biological growth. However, to be able to quantify the microclimatic effect on the indoor environment, there is a lack of knowledge about the airflow velocities behind furniture in dwellings.

In the present investigation the focus has been on the airflow pattern near a cold wall caused by the placement of the furniture. An earlier investigation by computational fluid dynamics (CFD) showed that different placement of furniture near colder external walls may affect the relative humidity in the microclimate and that the highest values were found when the furniture was placed directly on the floor and had a small distance to the wall (Mortensen et al, 2007a). There is a lack of empirical data of flow patterns behind furniture. Therefore, a number of different cases were used here, to study the effect of the distance between the furniture and the wall in combination with examination of the impact of the distance between the furniture and the floor. The distance between the furniture and the floor was an imitation of furniture elevation from the floor by use of legs as support. The investigation was performed by Particle Image Velocimetry, PIV. The results will provide empirical data of expected airflow velocities in such situations, and may be used as validation of computational fluid dynamics simulations. The intention of the current paper is that it should provide knowledge about the airflow patterns behind furniture placed in the vicinity of exterior walls.

Particle Image Velocimetry

Particle image velocimetry (PIV) is a fairly easy way to visualize fluid flows by use of tracking particles. The method is non-intrusive apart from the particles and thereby it is ensured that the actual flow field is determined. The PIV technique works by comparing image frames of a flowing fluid containing tracer particles. A laser creates a light sheet and the scattering particles on it reflect the light. Then a digital charge coupled device (CCD) camera is used to capture the instant placement of particles. The camera is connected with the laser so an image frame is recorded when the laser pulse is triggered. When a double laser pulse is fired, the reflection of light from the particles is saved in two different images. Hence, two frames are taken with minute intervals, and then it is possible to rediscover the particles of the first frame in the second frame. The particle movement between two frames gives a visualization of the flow pattern.

PIV has been used for more than 20 years and during this time it has evolved drastically as summarized by Adrian (2005). Adrian particularly highlights the development of double pulsed laser systems and CDD cameras. PIV has been used for numerous applications from aerodynamics of aircrafts, cars, buildings and other structures in air to velocity measurements of water in pipe flows and micro-scale flows. Investigation of airflows in a whole room is almost impossible with PIV due to a limited field of view area, which is roughly 0.5 x 0.5 m² for common equipment. To overcome this problem Zhao et al. (2001) invented a new PIV system for full scale rooms but further research is needed to improve the technology. Another method is to use scale models as done by Posner et al. (2003) in a study of the influence of how obstructions influence airflows in a room. When using scale models it might even be more convenient to use water as working fluid instead of air since this decrease the velocities. The approach of using water as fluid medium has been used and showed good agreement with numerical simulations for air by Adeyinka and Naterer (2005). An earlier applications of PIV in building physics by Lee et al. (2002) concerned ventilation flows inside a 1/1000 scaled factory building. They used air as medium and found that the airflow was dependant of the location and size of opening vents, building arrangement, and outdoor direction and wind speed.

The air gaps that are investigated in this paper can be assumed to be comparable with flow between asymmetrically heated parallel plates, which is closely related to natural convection flows in open ended channels. Aung et al. (1972) studied natural convection flows in channels with asymmetric heating both numerically and experimentally but not with PIV. Habib et al. (2002) used PIV to investigate airflow between both symmetrically and asymmetrically heated vertical plates of 125 mm height with a gap width of 40 mm. They found that an asymmetrically heated channel with 10°C higher and lower than ambient temperature gave an upward flow near the hot plate and it had a wider boundary layer than the cold plate with downward flow. With the same equipment Ayinde et al. (2006) studied turbulent natural convection in a symmetrically heated channel also by PIV and found indication of significant diffusion rates of the normal Reynolds stresses towards the centre of the channel.

Outline of current paper

The objective of the present study is to clarify the behaviour of natural convection in microclimates between external wall and furniture with special focus on airflow patterns and velocities. To obtain the highest resolution of the investigated air gap of only 25 or 50 mm it was chosen to use PIV in a full scale room. Air was used as fluid medium and to ensure the right natural convection pattern caused by buoyancy effects. The instantaneous velocity vectors in a two-dimensional flow field were measured with particle image velocimetry (PIV), while the temperatures at the surrounding boundaries were measured by thermo-couples. This paper presents an investigation that imitates natural convection behind furniture in dwellings. This phenomenon was investigated by different cases of distance between the furniture and the wall in combination with different furniture leg heights.

METHODS

Test Room

A test room was set-up for Particle Image Velocimetry measurements on furniture near a colder external wall. An ordinary room with internal dimensions of 3.6 x 4.5 x 2.5 m³ was created inside a larger test facility. A chilled internal wall was built in the chamber, and a plexiglass box was positioned against that wall to imitate a cupboard placed next to an external wall in a real building. An air gap behind the plexiglass furniture allows room air to pass over the chilled surface and this imitates microclimates found in ordinary dwellings, see Figure 1. The dimensions of the furniture were 1.5 x 0.46 x 2.0 m³ (width x depth x height).

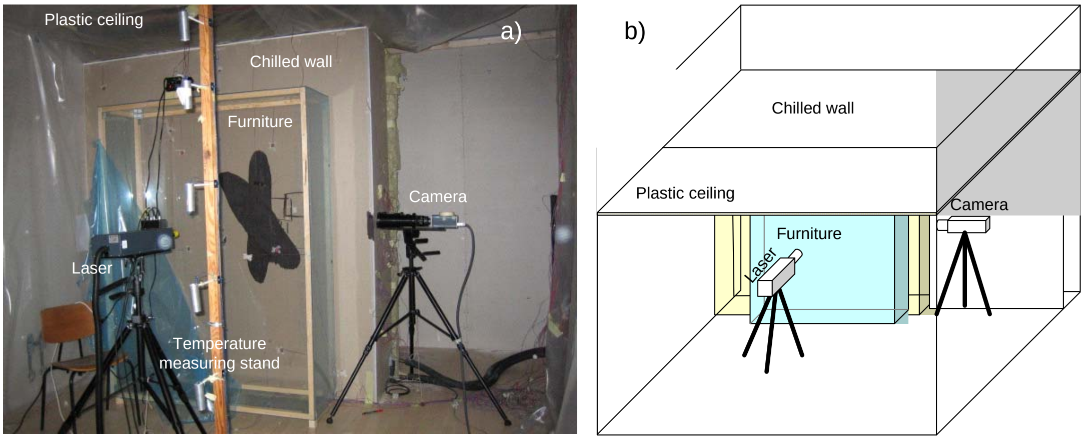


Figure 1. The experimental set-up, where the camera points into the air gap between the chilled wall and the furniture and the laser sheet is pointed in through the plexiglass furniture. a) A picture of the experimental set-up. b) A diagram of the PIV set-up.

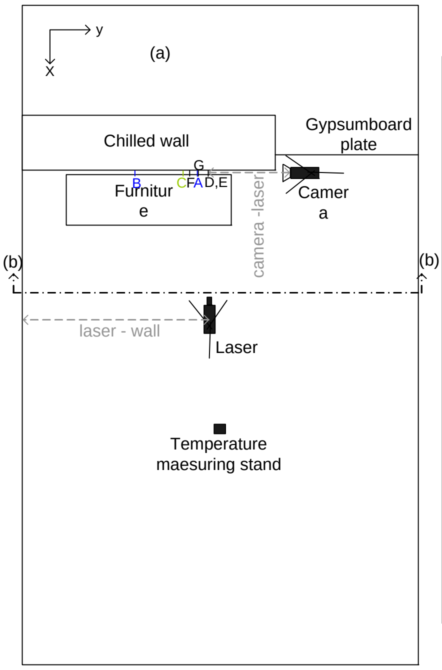
PIV Equipment

The two-dimensional flow field was measured by using a smoke of small oil droplets (glycol 0.1 – 1.0μm) as tracers and their motion was captured by a CCD camera (Dantec HiSense camera, 1024 x 1280 pixels). The tracer particles were illuminated by a light sheet of (about 3 mm in thickness) discharged from a water cooled double pulse Nd:YAG laser system (100 mJ/pulse). An external processor unit triggers signals to the camera and the laser, and coordi-nates the transportation of data from the camera to the computer processor. Further description of the equipment and measurements can be found in Mortensen et al. (2007).

Measurements

The measurements provide 2D velocity vector fields of the flow in the air gap behind the furniture. Figure 1 shows a picture and a perspective projection of the experimental set-up.

The study involved 2 different distances between the furniture and the wall in combination with 4 different distances between the furniture and the floor, in one of these the furniture is placed directly on the floor. The surface temperature of the chilled wall behind the furniture was constantly 16°C ± 0.4°C. During the measurements the average room temperature was 21.6°C ± 0.7°C. 8 different furniture positions where tested. The absolute camera and laser positions are described in Table 1 and illustrated in Figure 2.



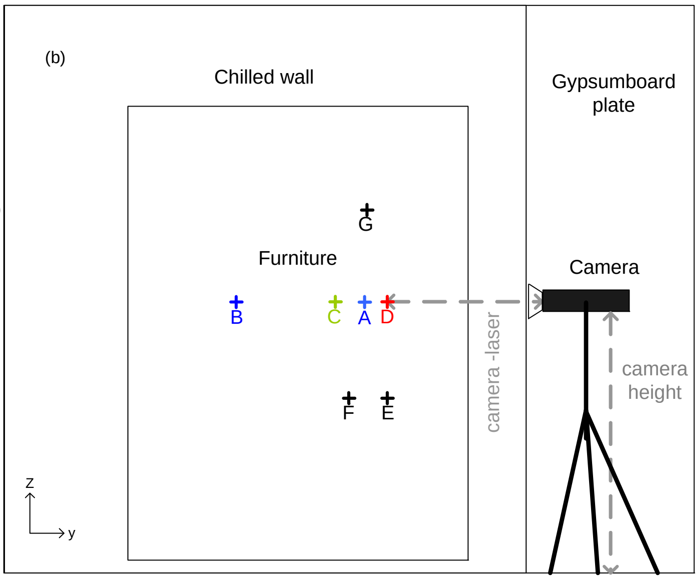


Figure 2. Part (a) show a plane of the measured PIV set-up and (b) show a front view of the room. The letters A-F show the measuring positions given in table 2. The distance between the camera and the laser sheet is shown for measuring position D.

Table 1. Description of different measuring positions with the PIV equipment. The physical image size changes with distance between camera and laser.

Posi-tion	Distance (mm) camera - laser	Image height (mm)	Camera height (mm)	Distance (mm) laser – wall	Measured furniture position
A	1050	124	1183	1570	1-8
B	1420	187	1183	1000	3-4
C	1200	136	1183	1440	3-6
D	920	106	1183	1670	1-8
E	930	113	770	1670	3-4
F	1080	130	770	1500	1-8
G	970	119	1595	1580	4

RESULTS & DISCUSSION

Only the vertical velocities in the vertical air gap will be shown and discussed, since the horizontal velocities are very small (magnitude of 2 % of the vertical velocities). The measured velocity field set positive upwards (z-direction in Fig. 2).

To obtain high quality PIV records a scattering particle concentration of 15 particles within each interrogation area is needed (Melling, 1997). The recorded images were post-processed to find the average value for the displacement that gave a velocity vector map. The used correlation method is an adaptive correlation (Westerwell et al., 1997; Scarano and Riethmüller, 1999), which avoid most errors in the flow field by comparing every vector with the average of the surrounding vectors. If the processed vector was more than 90 % different from the surrounding average the vector is removed.

In the figures with results the absolute camera position is given by its letter (see Table 1), and in most cases the measurements were taken after a stabilization time for the smoke in the room of 15 minutes. A number after the camera position indicates cases of longer stabilization time. All the presented results are based on average velocity vector maps. These results are averaged again for every velocity vector position in the height of the air gap except for the top 5 and bottom 5, because these may be influenced by errors caused by the physical limits of the image size. Therefore, the results are shown as single velocity curve profiles for every measuring position. By integrating the velocity profiles over the gap width, the local flow rates pr. width furniture has been calculated. The flow rates are given in the figure legends.

The results of all the measured velocities for the air gap of 25 mm between the furniture and the chilled wall are presented in Figure 3 and for the air gap of 50 mm in Figure 4.

All the measured velocity profiles for the different measuring positions seem to follow the same pattern. The maximum velocity and the highest flow rate always occur at measuring position F for both gap widths and for all 4 heights of the furniture (0-200 mm). Therefore, the flow is not assumed to be fully developed at least not for positions A and D. The flow rates for measuring position F is always higher than the other positions, and this indicates that air from the side of the furniture must be drawn in.

In Figure 3, for the 25 mm air gap the highest maximum velocity in the air gap is 0.42 m/s for measuring position F, when the distance between the floor and the furniture is highest, 200 mm. This also gives the highest flow rate. However, for 200 mm furniture leg height the maximum velocities for measuring position A and D are only 0.28 and 0.27 m/s respectively, which is almost the same as when the furniture is placed directly on the floor (0.27 m/s and 0.29 m/s) Elevation of the furniture by 50 or 100 mm furniture legs gives highest velocities. The observed flow behaves like flow between vertical plates heated asymmetrically, as shown by Aung (1972) because the height of the furniture is considerably larger than the width.

Another pattern is seen for the air gap of 50 mm in Figure 4 except for position A and D when the furniture is placed directly on the floor. The velocity increases with distance to the furniture followed by an almost linear increase of velocity until the maximum velocity is reached and then it decreases again getting closer to the chilled wall. This is similar to the results of Habib et al. (2002) who investigated asymmetrically heated plates where the cold plate and hot plate had a temperature difference of 10°C to the ambient air. They found a downward flow near the cold plate and a higher maximum velocity near the bottom of the plate than found at the top.

For both gap widths the maximum velocities are found closest to the chilled wall. This indicates that the boundary layer near the chilled wall dominates the flow, which is reasonable since the cold wall chills the air and the higher density makes it fall downwards.

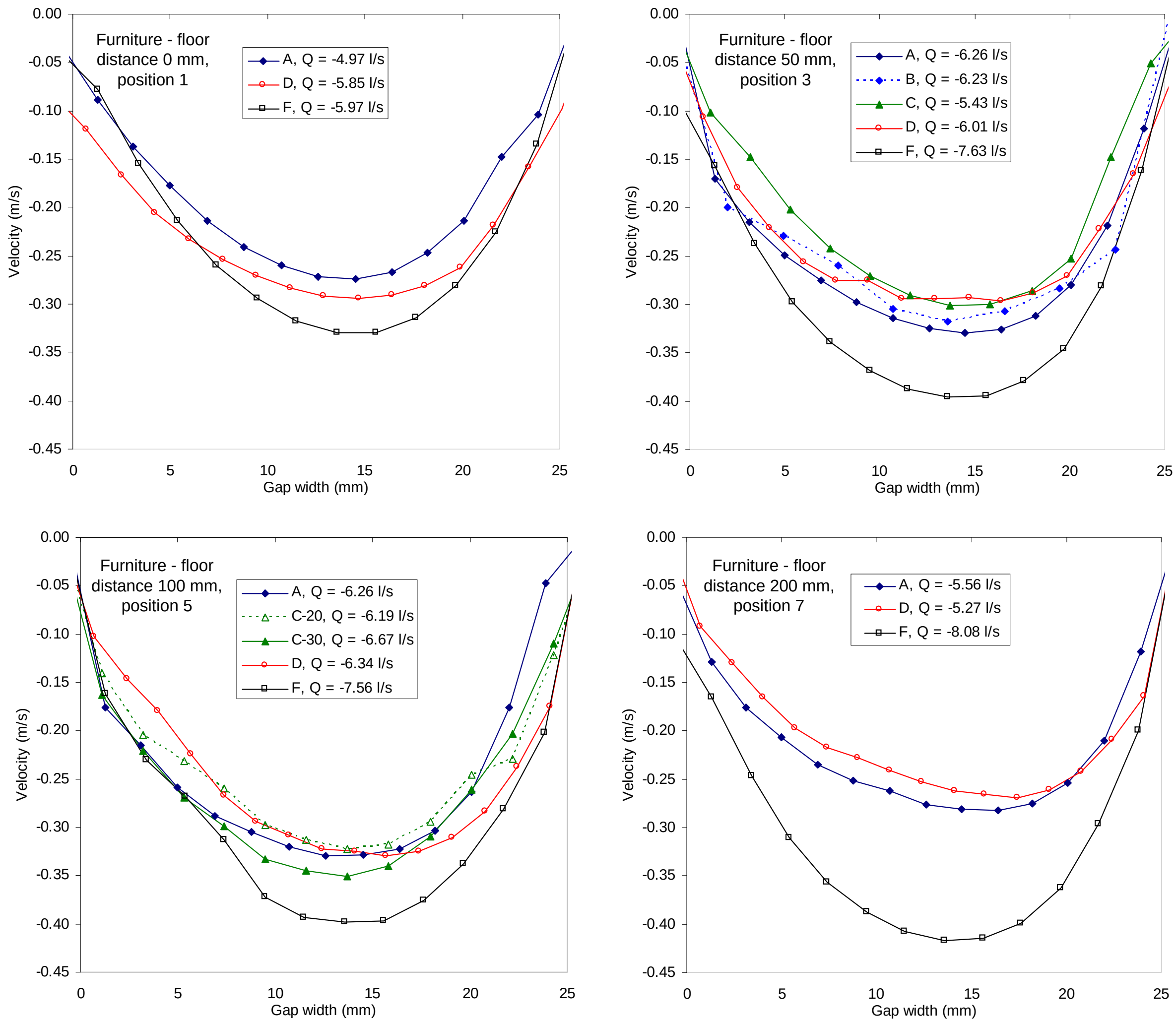


Figure 3. Measured velocities and flow rates (in legend) for the air gap of 25 mm between the chilled wall and the furniture. The letters A-F refer to different positions of the camera and laser (Table 1). The surface of the furniture is at 0 mm gap width and the chilled wall at 25 mm.

When the furniture is placed directly on the floor, the velocity profile generally seems to reach a lower maximum velocity than if the furniture is elevated by legs of 50 or 100 mm and the flow rates are also lower. For the 50 mm gap, the shape of the air velocity profile is different for position A and D when the furniture leg height is 0 mm, where the velocity grows with increased distance to the furniture until maximum is reached. The maximum is around 0.25 m/s and from this point a constant velocity continues until it starts to decrease near the chilled wall. The air must exit through the sides behind the furniture in a three-dimensional flow path since it cannot flow out underneath the furniture, but this was not recorded by the camera since the velocity measurements taken were two-dimensional.

For the narrow 25 mm gap, the maximum furniture leg height of 200 mm gives lower velocities for position A and D. Again, the only reason is a three-dimensional effect, which needs to be investigated further, but it may be due to increased turbulence in the region under the furniture. This could indicate that there is a limit to the effect of the furniture leg height if the goal is to ensure as high velocity or flow rate behind the furniture as possible.

The lowest maximum velocity at 0.25 m/s was found for the 50 mm air gap at position A and D with leg heights of 0mm and position A for 200mm. Even the lowest maximum velocity is high enough to cause draught so the furniture actually does not significantly limit the airflow behind it. The assumed concern that furniture limits the airflow cannot be confirmed. Furthermore, the results indicate that there may be a linear correlation between the gap width behind furniture and flow rates.

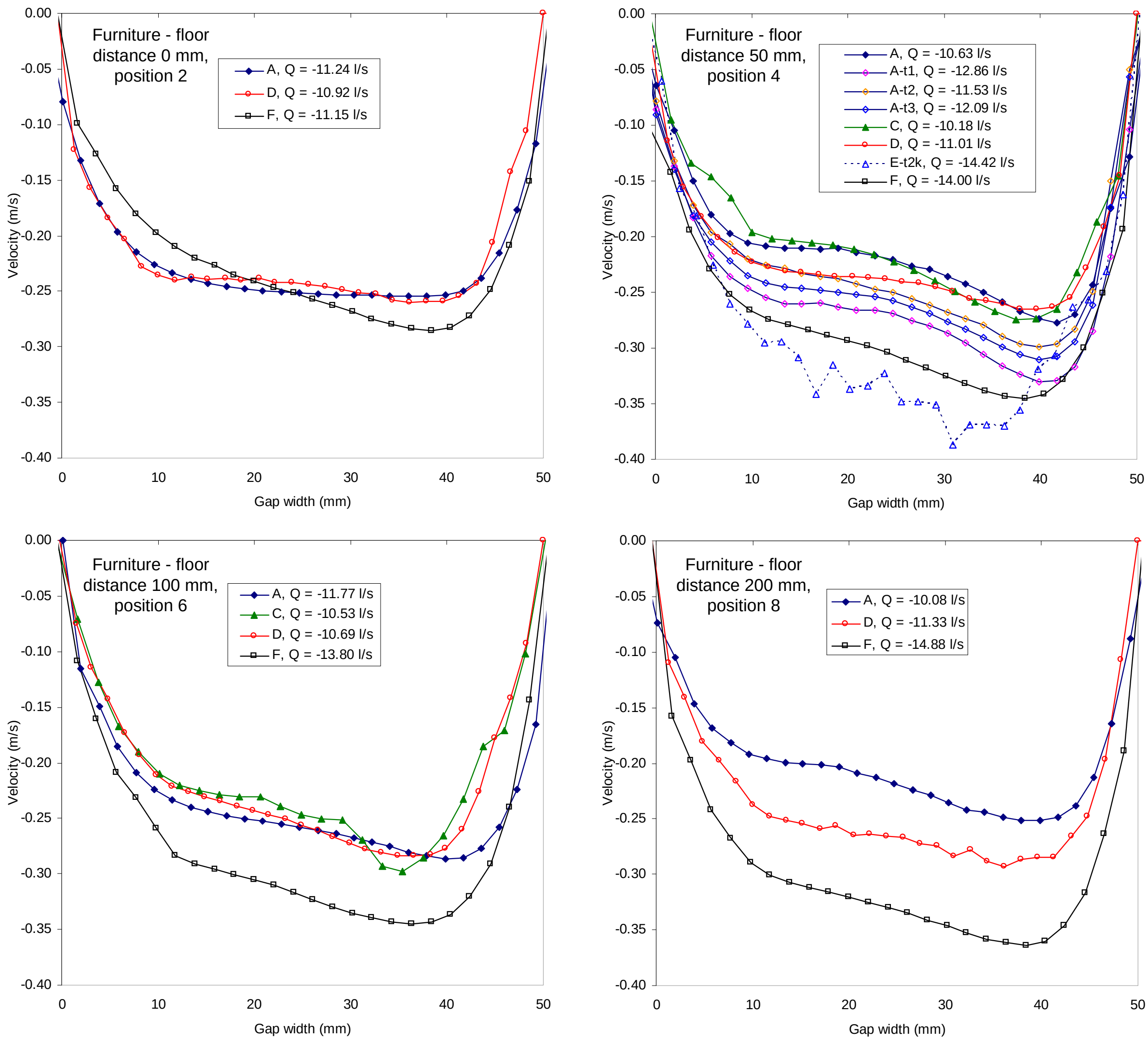


Figure 4. Measured velocities and flow rates (in legend) for the 50 mm air gap between the chilled wall and the furniture. The letters A-F refer to different positions of the camera and laser. The surface of the furniture is at 0 mm gap width and the chilled wall at 50 mm.

Errors

Factors for resolving the error of the PIV measurements are: Particle and image size, interrogation area, velocity gradients, number of particles, instrumentation performance, and computational errors like rounding and truncation, further information is given by Mortensen et al. (2007). Most errors are caused by reflections and global particle distribution in the test facility.

CONCLUSION

This paper presents an investigation of the airflow pattern in a small air gap between a chilled wall imitating an exterior wall and a piece of furniture placed next to it using PIV. The results provide empirical data for the velocities behind furniture in dwellings. This data can be useful for comparison to numerical simulation of airflow behind furniture.

The measured and analysed two-dimensional results indicate that the flow in the air gap was not fully developed. The results were also found to be repeatable. The two investigated gap widths of 25 and 50 mm showed different patterns of velocities, but they both seem to be dominated by the boundary flow near the chilled wall. For all the tested measuring positions it was found that the flow rate is increased when the gap is expanded from 25 mm to 50 mm. Furthermore, there is an indication of higher flow rates if the furniture is elevated from the floor but the leg height is less than 200 mm. However, this needs further investigation.

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